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MARS RECONNAISSANCE ORBITER NAVIGATION STRATEGY FOR SUPPORT OF INSIGHT LANDER'S ENTRY, DESCENT AND LANDING SEQUENCE

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The Mars Reconnaissance Orbiter (MRO) provided primary relay support for surface operations of the InSight mission immediately after it landed on Mars on November 26, 2018. To position MRO for relay support during InSight Entry, Descent and Landing (EDL), two propulsive maneuvers were performed in August and October 2018. This paper documents the maneuver strategy employed by the MRO Navigation Team to support the InSight EDL sequence.

INTRODUCTION

The Mars Reconnaissance Orbiter (MRO), in its fourth extended mission orbiting Mars, provided telecommunication relay support to NASA's InSight mission during the Entry, Descent and Landing (EDL) sequence on November 26, 2018. MRO also supplied relay support during the EDL sequences of other spacecraft such as the Mars Phoenix Lander in May 2008,[1] the Mars Science Laboratory (MSL) in August 2012,[2] and more recently ESA's ExoMars EDL Demonstrator Module (EDM) in October 2016.[3] Like EDM EDL, MRO's support of InSight EDL occurred during the peak atmospheric density season. This paper will discuss the MRO navigation strategy, as well as the operational challenges, to support InSight EDL in achieving the EDL phasing requirements. For telecommunication and imaging support during the InSight EDL event, the InSight Project requested that MRO transition to a 2:52 PM Local Mean Solar Time (LMST) at the orbit ascending node at the time of InSight EDL; 3:00 PM is the nominal Primary Science Orbit (PSO) LMST. InSight also requested post-landing relay support from MRO for surface operations. The requirements for MRO's support of InSight EDL were as follows:

- The MRO orbit LMST at InSight EDL must be between 2:42:00 PM and 2:52:30 PM.
- MRO must phase within ± 30 seconds of the specified InSight entry epoch (within ± 1.6 degrees of a requested latitude target specified at InSight entry).

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MRO nominally implements a propulsive maneuver in one of two standard maneuver attitudes: in-plane (spacecraft velocity vector) or out-of-plane (spacecraft angular momentum vector). Typical PSO maintenance maneuvers (Orbit Trim Maneuvers, or OTMs) are executed in-plane for apses height control; most have been performed at orbit periapsis to raise orbit apoapsis. These maneuvers are used to maintain the PSO ground track walk (GTW) repeat error between ±60 km. Orbit LMST control (inclination change) is achieved via out-of-plane maneuvers, referred to as Orbit Change Maneuvers (OCMs). Orbit phasing is accomplished through in-plane maneuvers, referred to as Orbit Synchronization Maneuvers (OSMs). These phasing control maneuvers are used to produce a change in MRO orbit period that, over a given duration, produces a desired total MRO orbit down-track timing change.

In March 2017 an OCM was performed to achieve the LMST requirement for InSight EDL. With Mars atmospheric drag ΔVs larger than at the time of MSL EDL, the orbit phasing of MRO with the InSight EDL sequence proved to be demanding. Two OSMs were performed in August and October 2018, prior to InSight landing, to place MRO at the requested EDL target time. A contingency OSM was also planned in November just weeks prior to InSight EDL but was cancelled due to the phasing requirement of ±30 seconds being met by the prior OSMs. This paper will discuss the challenges faced in the designs of these maneuvers which required a close tracking of the predicted timing offset from the InSight relay target given the expected larger down-track uncertainties.

MRO MISSION OVERVIEW

MRO completed several missions at Mars: the Primary Science Phase, the Extended Science Phase, and three extended missions (EM1, EM2, and EM3). MRO is currently in its fourth extended mission (EM4) which ends in September 2019. As an asset of the Mars Exploration Program, MRO continues to perform science observations and provide telecommunication relay support to the Mars Exploration Rover since January 2004 and the Mars Science Laboratory since August 2012.[2] It also supplied relay support to the Mars Phoenix lander in May 2008, observed the close flyby of Comet Siding Spring at Mars in October 2014[4] and imaged the ExoMars lander Schiaparelli in October 2016.[3,5] In addition to supporting InSight EDL, MRO plans to provide telecommunication support for the EDL phase of NASA's Mars 2020 mission in February 2021.[6]

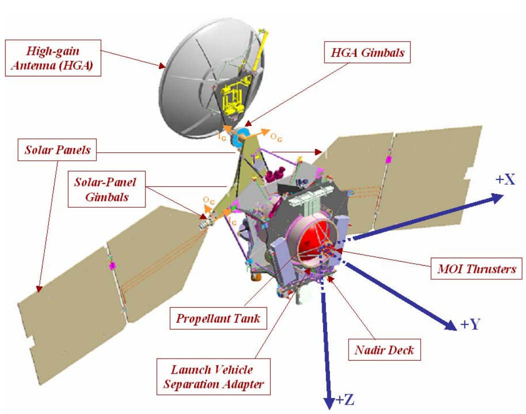


Figure 1: Diagram of the MRO spacecraft.

MRO Spacecraft

The spacecraft axes, as shown in Figure 1, are defined such that the X-axis is directed along the velocity vector, the Z-axis is along the nadir direction, and the Y-axis completes the triad. The six engines for MOI and the six Trajectory Correction Maneuver (TCM) thrusters are located along the +Y direction. The large solar panels are on the $\pm$X axes, canted 15 deg towards +Z. The 3-meter diameter High Gain Antenna (HGA) is located opposite the nadir deck, where the majority of the science instruments are located. During science operations, the nadir deck is configured towards Mars. Both solar panels and HGA swivel to track the Sun and Earth, respectively. MRO is gravitygradient stabilized to sustain the nadir-to-planet orientation. Spacecraft attitude is maintained by the Reaction Wheel Assembly (RWA); this consists of three 100 Nms wheels mounted perpendicular to each other, augmented by a fourth redundant wheel in a skewed orientation. The monopropellant propulsion subsystem uses three sets of thrusters: the aforementioned MOI and TCM thrusters, and the Attitude Control System (ACS) thrusters. The TCM thrusters have been used for Orbit Trim Maneuvers (OTMs) since February 2007. The ACS system uses balanced thrusters where the thruster pairs are fired together and arranged such that a net zero ΔV is imparted. The spacecraft bus built by Lockheed Martin provides a stable platform for the payload science instruments. These instruments, mounted for observation on the +Z axis of the spacecraft (nadir deck), are used to perform remote sensing of the Martian atmosphere, surface, and subsurface. They include the High Resolution Imaging Science Experiment (HiRISE) camera, the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM), the Mars Climate Sounder (MCS), the Mars Color Imager (MARCI), the Context Camera (CTX), the Shallow Subsurface Radar (SHARAD), and the Electra ultra-high-frequency (UHF) engineering payload. High resolution imagery is performed using the HiRISE camera. This key resource is able to supply imaging of orbiting or landed assets on Mars as well as observe possible future landing site locations. Relay telecommunication support in the UHF frequency range is provided by the Electra instrument.

MRO Primary Science Orbit

The Primary Science Orbit (PSO) for MRO operations is a 252 km $\times$ 317 km altitude, sun-synchronous orbit with the periapsis frozen over the south pole and the ascending node at 3:00 PM $\pm$ 15 minutes. The osculating orbital elements are shown in Table 1 for the MRO orbit containing the InSight EDL event. The orbit is designed to exactly repeat after 4602 revolutions in 349 sols (1 sol = 1.0275 days), with separation between ground tracks of less than 5 km at the equator. The near-repeat cycle used for science planning is a 211-orbit cycle (16 sols) that walks about 0.5 deg (32.5 km) in longitude westward from the previous cycle. The orbit maintenance is done based on this near-repeat cycle via propulsive maneuvers.

Table 1: Osculating Orbital Elements on November 26, 2018 (MRO Orbit 57820).

Periapsis Epoch: 26-Nov-2018 19:18:43.812 ET	
Semi-Major Axis (a)	3648.0101 km
Eccentricity (e)	0.0057
Inclination (i)	92.5883°
Argument of Periapsis (ω)	270.0388°
Right Ascension of Node (Ω)	194.4081°
True Anomaly (v)	0.0°
Additional Orbit Information	
Ascending Equator Crossing Epoch (Near InSight EDL): 26-Nov-2018 19:46:26.637 ET	
Apoapsis Epoch: 26-Nov-2018 20:14:42.280 ET	
Period (T)	111.4962 min
Periapsis Altitude (H_p)	250.9336 km
Apoapsis Altitude (H_a)	316.8581 km

INSIGHT MISSION OVERVIEW

The Interior Exploration using Seismic Investigations, Geodesy, and Heat Transportation (InSight) mission is a robotic lander that was designed to conduct in-depth studies of the Martian interior. The mission objectives are to measure Mars' seismic activity in order to build accurate 3D models of the interior; and to measure the internal heat flow using the HP^3 experiment* which will allow scientists to better understand Mars' early geological evolution. The spacecraft launched from Vandenberg Air Force Base on May 5, 2018, and after a 6.5 months journey through space, it landed on Mars on November 26, 2018.

*HP^3 stands for the Heat Flow and Physical Properties Probe.

EDL is a critical phase of the mission and continuous communication with the Earth is one of the mission requirements. At the time of EDL the one-way light time between Earth and Mars exceeded the duration of the EDL sequence, which made any ground control interaction impossible. However, continuous communication with the spacecraft provides a valuable time history of data that can be used to aid future mission planning as well as failure investigations, should that have occurred.

Throughout the cruise phase of the mission the spacecraft communicated with the Deep Space Network (DSN) on Earth using the X-band antenna located on the cruise stage. The cruise stage was jettisoned seven minutes prior to entry interface, and this also marked the loss of the X-band communication link with the Earth. The only antenna on the backshell (see Figure 2) is the UHF wrap-around antenna (WPA). Thus the UHF carrier-only signal is of limited use, and if a failure had occurred, its presence or absence and the Doppler shift of the signal could explain what happened but the reason for it could not be deduced.

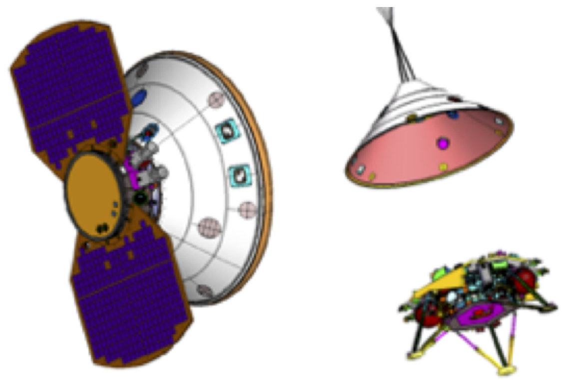


Figure 2: InSight before entry (left) and just after lander separation (right)

The InSight mission relied on the Mars orbiters and the Mars Cube One (MarCO) spacecraft for relaying the telemetry to Earth during EDL. In this paper, the role that MRO played in relaying the InSight data during EDL is discussed.

SELECTION PROCESS FOR INSIGHT EDL TARGET

MRO had been identified as the prime NASA relay service provider for the InSight lander. It was expected to provide support for up to 7 days after EDL, which would aid the UHF and data flow performance analysis. This level of support included enabling successful forward- and return-link data transfers to InSight. The MRO project had agreed to maintain MRO's orbit for the relay support for at least the first 7 days (prime support period) of the InSight surface mission and continue to support surface operations thereafter. Per MRO-InSight Navigation OIA-093 (Operational Interface Agreement), the final tolerances allowable in achieving the prescribed targets were:

- Time of target areocentric latitude crossing (+/- 30 seconds), equivalent to 1.6 degrees in areocentric latitude
- The targeted LMST is 2:52 PM
- The achieved LMST should be not later than 30 sec after the LMST target and not earlier than 10 min before the LMST target.

The EDL Relay Target Files (ERTFs) which InSight supplied to the MRO Navigation Team on a regular basis contained the requested relay target. ERTF-15 provided the requested phasing target that was used in the last phasing maneuver design. ERTF-20 was the final ERTF that gave the last prediction of the landing site just prior to InSight EDL. See Appendix A for the ERTF delivery history and the contents of ERTFs 15 and 20.

The InSight landing site was 4.50° S, 135.94° E in the Elysium Planitia region, near the Curiosity landing site (4.59° S, 137.44° E). The final predicted MRO ground track prior to EDL and the InSight landing site are shown in Figure 3, as well as the landing sites for the Opportunity and Curiosity rovers. MRO's position at the entry target time as specified by ERTF-15 is also indicated.

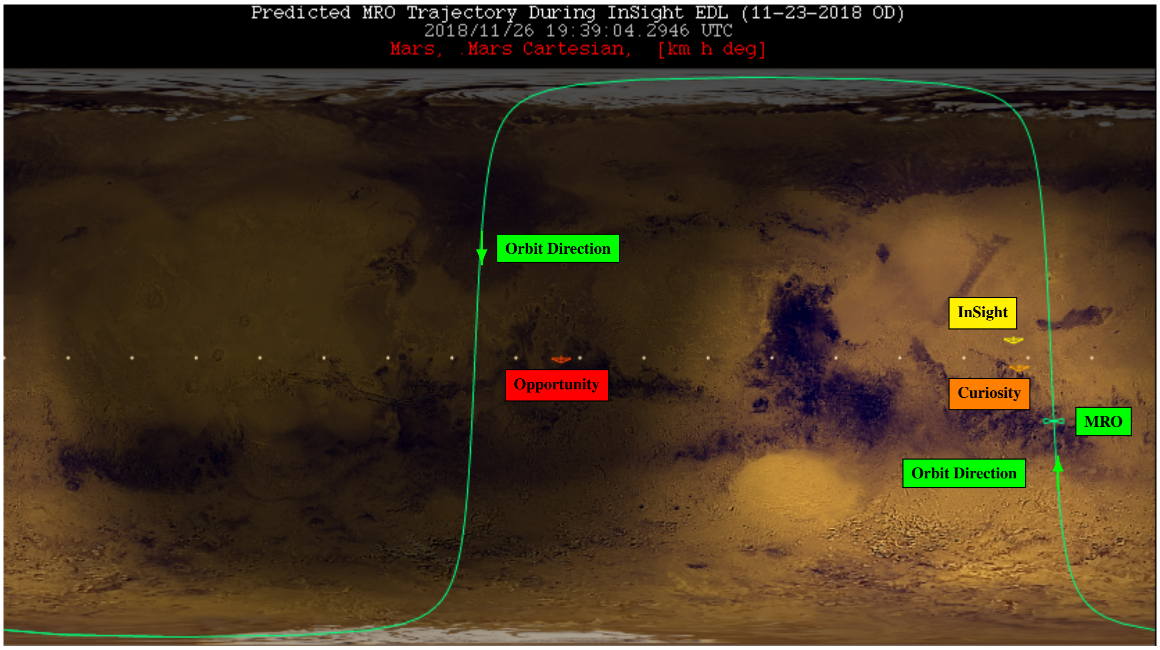


Figure 3: MRO Trajectory Ground Track During InSight EDL and InSight Landing Site. *Green curve is MRO ground track during EDL, green satellite icon is MRO position at target latitude, yellow icon is InSight landing site, orange icon is Curiosity landing site, and red icon is Opportunity landing site.*

INSIGHT EDL PHASING STRATEGY

The MRO Navigation Team developed a maneuver plan for phasing MRO to the InSight EDL target. The maneuver strategy was designed to mitigate uncertainties due to atmospheric drag and other orbital effects. A phasing approach with three maneuvers was implemented for correcting the timing offset. This approach would minimize the chance of overshooting the phasing target. Just prior to the first maneuver, the predicted phasing offset from the target was about 55 minutes early, or approximately one-half of MRO's orbital period ($\sim$112 minutes). Orbit phasing is accomplished via in-plane OTMs, also referred to as Orbit Synchronization Maneuvers (OSMs). Ultimately, only two OSMs performed in the pro-velocity direction were needed to increase MRO's orbit period so that it would reach the target within the $\pm$30 seconds phasing requirement.

Anticipated Atmospheric Drag and Navigation Timing Uncertainties

The atmospheric density variation is the largest contributor to errors in the MRO navigation accuracy, barring a significant maneuver execution error.[5] As shown in Figure 4, the atmospheric drag was anticipated to be much higher leading up to the InSight landing than when phasing was performed to support the EDL sequences of the Phoenix and MSL missions and the risk mitigation efforts due to the Comet Siding Spring flyby of Mars.[4] However, it was comparable to the anticipated atmospheric drag leading up to the time of Schiaparelli (EDM) support; maneuver planning was done assuming a drag ΔV of 0.45 mm/s per orbit for the first phasing maneuver and later lowered to 0.35 mm/s per orbit for subsequent maneuvers (see the navigation timing uncertainties plots leading to EDL in Figure 5). With the 0.45 mm/s per orbit assumption, the data cut-off (DCO) for the third phasing maneuver planned (OSM-3) was 18 days prior to EDL (see Figure 5a) in order to meet the $\pm$30 seconds requirement, which is only six days prior to the execution of the maneuver. Nominally, the DCO for an MRO maneuver is nine days prior to execution to allow time for subsystem assessments and scheduling. Following the execution of OSM-1, the drag ΔV assumption was lowered to 0.35 mm/s per orbit which in turn allowed the DCO to be increased to 21 days prior to EDL (see Figure 5b) and still meet the $\pm$30 seconds requirement, returning to the nominal nine days for maneuver processing. Note that phasing was only corrected up to the navigation uncertainty level at a given maneuver opportunity to avoid potentially overshooting the target time. When planning the phasing strategy it was also recognized that the maneuver ΔV should not go below the minimum control capability of 20 mm/s.

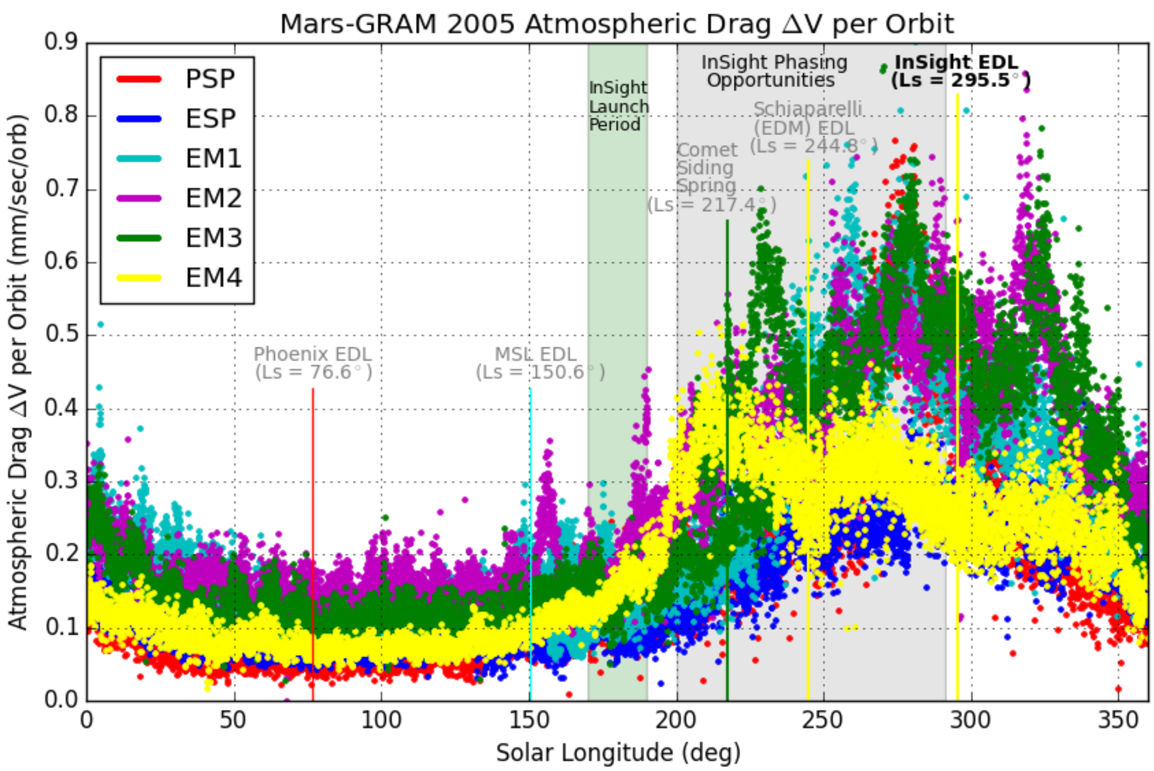
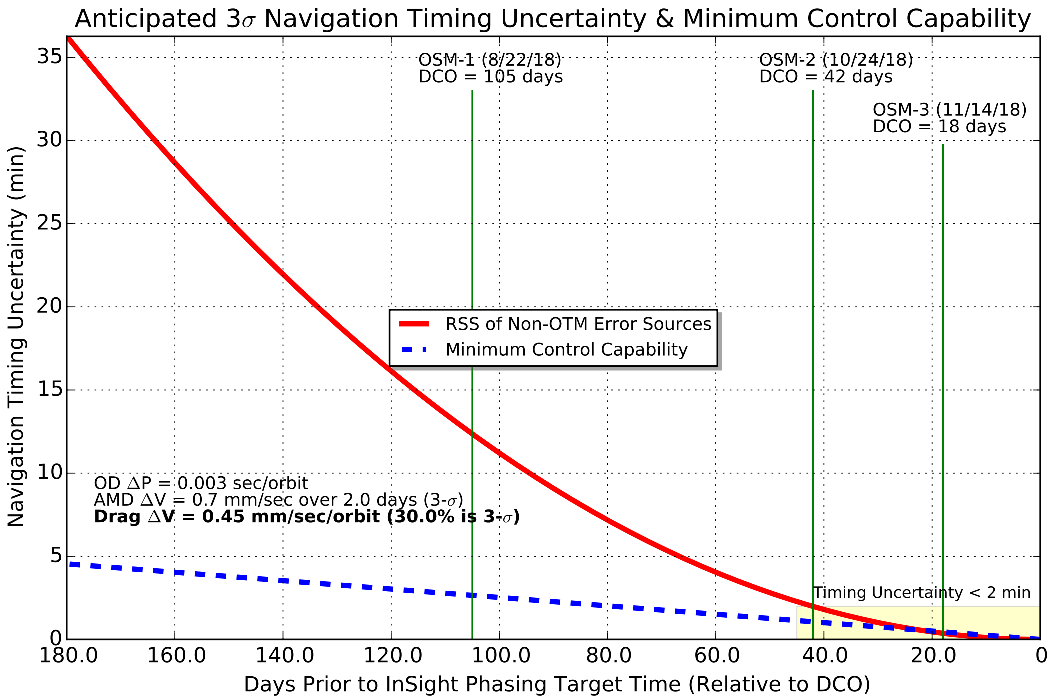
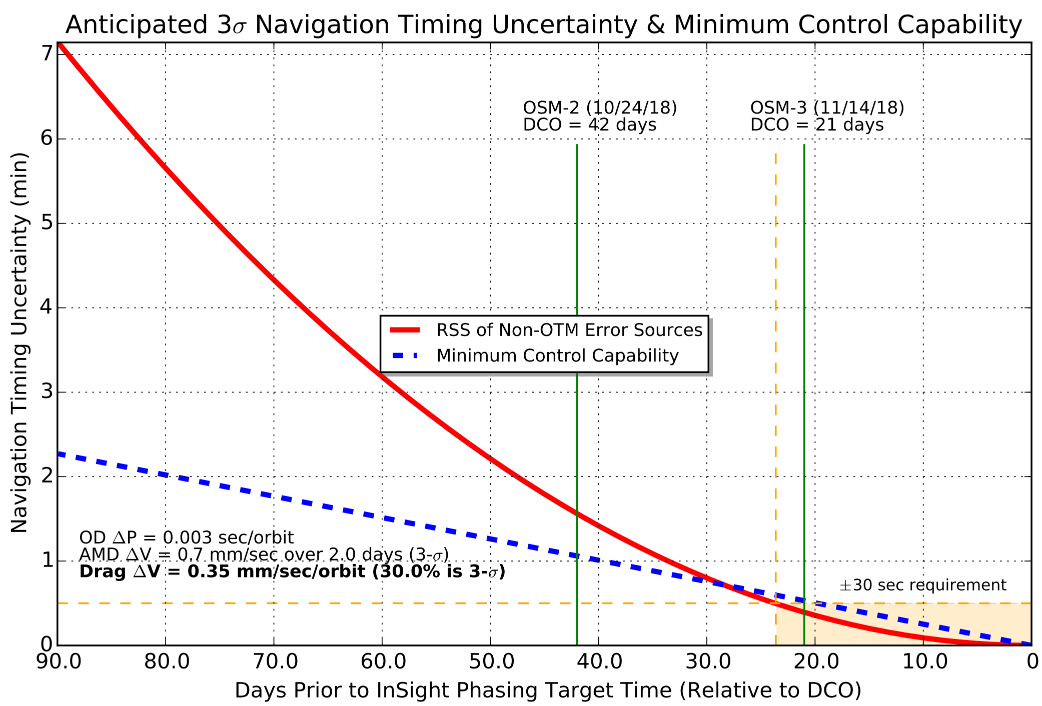


Figure 4: Atmospheric Drag ΔV Experienced by MRO through December 2018. *By mission phase: PSP = Primary Science Phase, ESP = Extended Science Phase, EM = Extended Mission (1-4)*



(a) Navigation Timing Uncertainties (3-σ) at the Time of OSM-1 (Drag ΔV = 0.45 mm/s/orbit)



(b) Navigation Timing Uncertainties (3-σ) at the Times of OSMs 2 & 3 (Drag ΔV = 0.35 mm/s/orbit)

Figure 5: Navigation Timing Uncertainties (3-σ) Prior to InSight EDL Target Time

Solar Cycle

In order to reasonably predict the atmospheric density scale factor (DSF) when planning phasing maneuvers it was important to consider the solar cycle, as the Sun's activity has a significant effect on the volatility of Mars atmospheric behavior. Due to the Sun's activity being near a minimum, significant jumps in the DSF were not expected in spite of the high density period. The solar cycle profile from the International Space Environment Service (ISES) is provided in Figure 6. As a comparison the DSF history from the previous Mars year was used for the comparable time period (similar solar longitude, L_S) as seen in Figure 7. Since the second phasing maneuver DCO was about 42 days prior to EDL, the DSF change for the similar period at the previous Mars year was also considered. Thus 0.62 was chosen as the mean DSF when designing OSM-2.

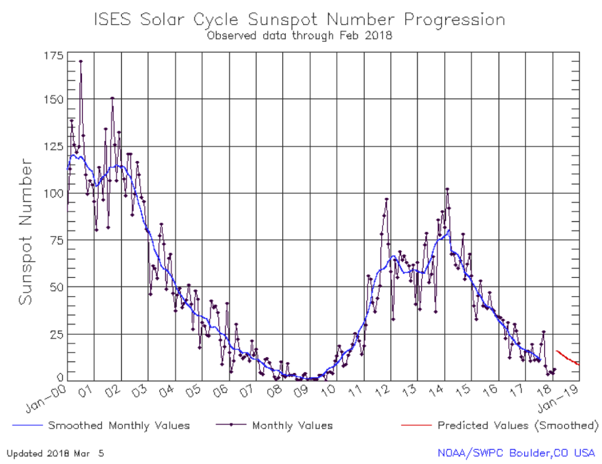


Figure 6: Solar Cycle Profile Through February 2018

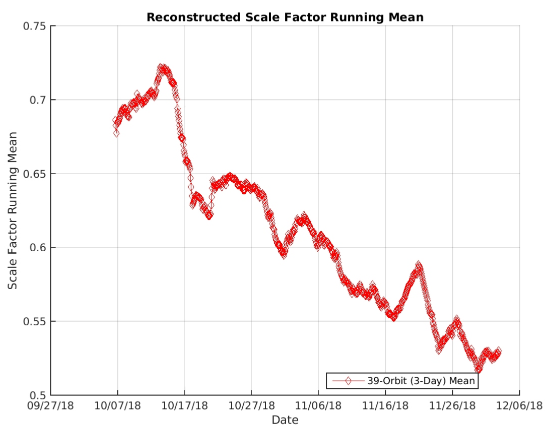


Figure 7: Reconstructed Density Scale Factor Running Mean Through December 2018

Phasing Maneuvers: OTM-50 and OTM-51

As previously mentioned, orbit phasing is accomplished via in-plane OSMs. OTM-50 (OSM-1), the first of two pro-velocity OSMs, was executed on August 22, 2018, about three months prior to the InSight landing. When the maneuver strategy was initially planned, the predicted phasing offset from the target time defined by ERTF-01a (see Table 6 in Appendix A) was about 47 minutes early. However, at the time of the final maneuver design (one week prior to the OTM-50 execution) the phasing offset increased to about 55 minutes early. This may be attributed to the evolution of the orbit determination (OD) and the Mars dust activity – Planet Encircling Dust Event (PEDE). Limiting the phasing correction to the navigation uncertainty ($\sim$12.5 minutes) at the OTM-50 DCO of 105 days from the InSight EDL target time (see Figure 5), OTM-50 was designed to remove about 43 minutes of phasing offset. This maneuver performed nominally, but with a slight overburn of 1.5%. Table 2 lists the estimated phasing errors at the InSight EDL target prior to and following each phasing maneuver, as well as the expected down-track timing uncertainties at each maneuver opportunity. Targets given in ERTF-10 and ERTF-15 were used to design OTM-50 and OTM-51, respectively.

Table 2: History of Phasing Offset from InSight EDL Target Time

	OTM-50 (OSM-1)	OTM-51 (OSM-2)	OSM-3	InSight EDL Target
Event Date	8/22/2018	10/24/2018	11/14/2018	11/26/2018
OSM Execution Prior to InSight EDL	96 days	33 days	12 days	
OSM ΔV (Designed)	0.3384 m/s	0.0568 m/s	*cancelled*	
Target File	ERTF-10	ERTF-15		ERTF-15
InSight EDL Phasing Offset (Pre-OSM)	55.23 min early	2.41 min early		
InSight EDL Phasing Offset (Post-OSM)	10.74 min early	0.03 sec early		**8.41 sec late**
InSight EDL Phasing Correction via OSM	**44.5 min early**	**2.4 min early**		**(reconstructed)**
Down-Track Timing Uncertainty (3-σ)	12.5 min	1.6 min	18.0 sec	
OD DCO for OSM	8/13/2018	10/15/2018	11/8/2018	
DCO Prior to InSight EDL Target	105 days	42 days	18 days	

After completion of OTM-50 a timing offset of about 11 minutes remained. This was to be corrected via OTM-51 (OSM-2) on October 24, 2018. This maneuver over-performed by 3.2% placing MRO early by 0.03 seconds from the target time. This was well within the down-track timing uncertainty of 1.6 min (42 days prior to InSight EDL). The MRO trajectory reconstruction done following the InSight landing indicated that the spacecraft was actually late at the target location by about 8.41 seconds. As expected, the atmospheric density variations, etc., contributed to this slight change in the phasing offset. A summary of the design and reconstructed ΔVs of the maneuvers to achieve 2:52 PM LMST (OTM-48), for GTW control (OTM-49), to achieve the phasing target (OTM-50 and OTM-51), and the post-InSight EDL PSO recovery and LMST change maneuver (OTM-52) discussed in a later section is given in Table 3.

Table 3: MRO Maneuver History for InSight EDL Phasing and Science Operations Recovery

Maneuver	Maneuver Epoch (UTC SCET)	Orbital Apsis/ Node	Data Source	ΔV (mm/s) Value	ΔV $\lvert err \rvert$	Right Ascension (deg) Value	Right Ascension $\lvert err \rvert$	Declination (deg) Value	Declination $\lvert err \rvert$	Duration (sec) Dur	Duration $\lvert err \rvert$
OTM-48 (OCM-3)	22-Mar-2017 13:38:40	DEqX	Recon	3203.3	6.6	191.02	0.36	13.11	0.62	45.1	0.7
			Design	3196.7		191.37		12.49		45.8	
OTM-49	13-Sep-2017 13:34:55	Apo	Recon	217.7	1.7	197.52	0.03	19.74	0.04	10.0	0.2
			Design	216.0		197.55		19.78		9.8	
OTM-50 (OSM-1)	22-Aug-2018 12:25:50	Peri	Recon	343.8	5.3	196.27	0.22	19.01	0.08	15.1	0.0
			Design	338.4		196.48		19.09		15.1	
OTM-51 (OSM-2)	24-Oct-2018 13:01:46	Peri	Recon	58.6	1.8	225.65	0.35	3.19	0.22	2.9	0.2
			Design	56.8		226.01		2.96		2.7	
OSM-3	14-Nov-2018	Peri	.... *Contingency maneuver if $\pm$30 sec requirement not met*								
OSM-3C	19-Nov-2018	Peri	.... *Contingency maneuver if $\pm$30 sec requirement not met*								
InSight EDL Target Time: 26-Nov-2018 19:40:13.4776 ET SCET											
OTM-52 (OCM-4)	12-Dec-2018 14:18:23	DEqX	Recon	-	-	-	-	-	-	-	-
			Design	1403.0		1.23		-60.50		20.3	

Atmospheric drag reduces the energy of MRO in its orbit. This reduces the orbital period and increases the ground track walk (GTW) error. Pro-velocity maneuvers increase the semi-major axis, which extends the orbital period. Thus this maneuver approach also aided the GTW control error limited only by the phasing required by InSight EDL support (see Figure 8). Reference 6 provides a more detailed discussion of the GTW maintenance strategy employed by MRO.

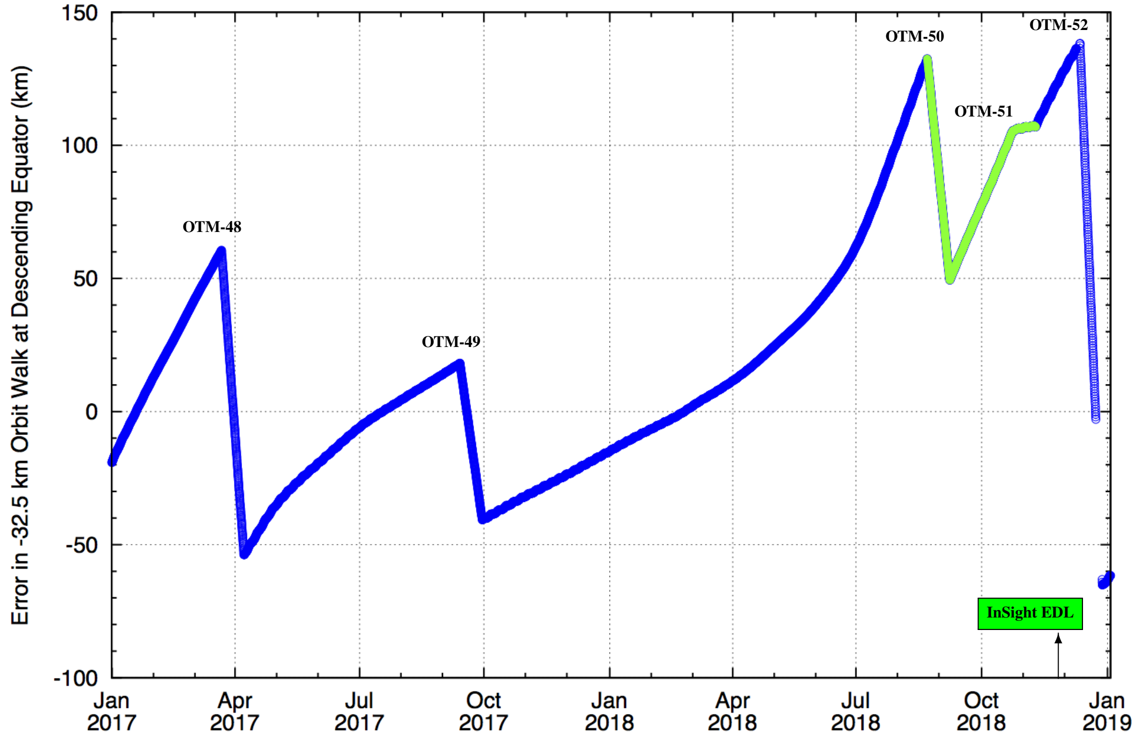
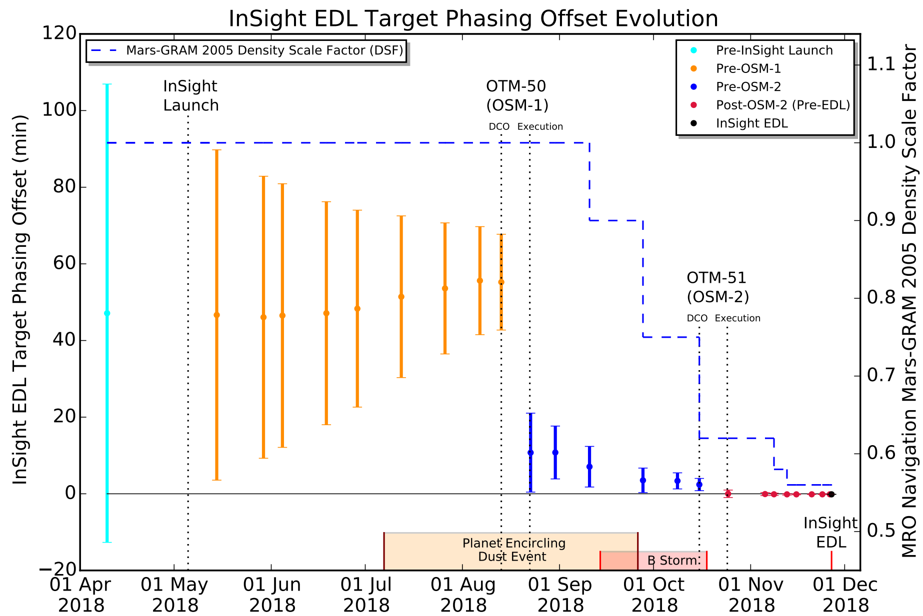


Figure 8: MRO Orbit Ground Track Walk Repeat Error from January 2017 – December 2018. *GTW control (blue), pro-velocity phasing for InSight EDL (green).*

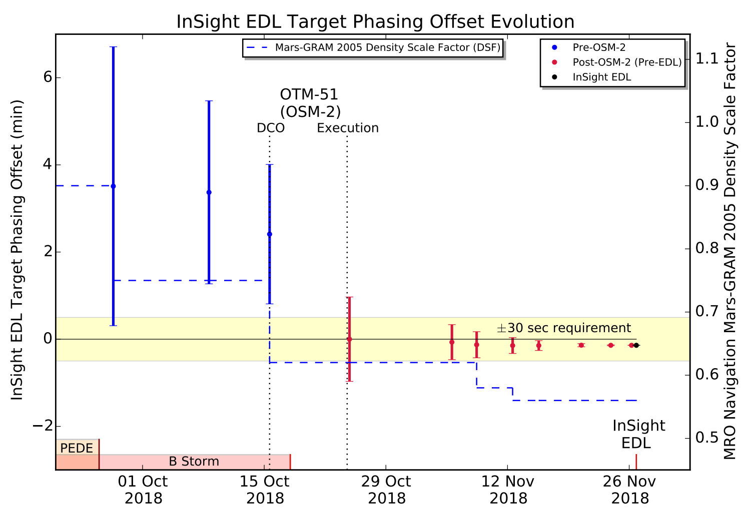
Initially, a three-maneuver strategy was considered as the baseline plan for phasing to the InSight EDL target conditions. However, due to the third maneuver placed on November 14, 2018 (12 days before EDL), the Navigation Peer Review board recommended assessing EDL link degradation if the phasing requirement was violated (e.g. 60 sec). If this was insignificant, then it would give the InSight and MRO projects the opportunity to consider skipping the third maneuver in the case the benefit outweighed the risk of doing a maneuver in close proximity to the EDL time. Subsequent link analysis by the InSight Team indicated no significant link degradation. Since the prediction of the remaining phasing offset following OSM-2 stayed well within the required phasing limits, OSM-3 and its backup were eventually cancelled (see Table 3).

Phasing Offset Evolution History

MRO Navigation started receiving from the InSight Navigation Team the InSight EDL target files (ERTFs) starting a month prior to the InSight launch (May 5, 2018). Post-launch ERTFs were provide to MRO Navigation on a nearly 2-week frequency. The MRO Navigation Team continued tracking the InSight phasing offset after the Insight launch until the day before EDL. This included removing some timing offset with the first phasing maneuver OTM-50 on August 22, 2018 and the remaining offset with the second phasing maneuver (OTM-51). The atmospheric density variations and other orbit determination inaccuracies were expected to affect the phasing offset. As the orbit determination of MRO is done at least twice per week, it was possible to periodically assess the current offset from the final desired target time. These offsets were reported to both the MRO and InSight projects. The phasing offset values and associated navigation errors are plotted in Figure 9. A negative sign in the offset indicates being late and a positive sign being early. For example, prior to the second phasing maneuver OTM-51, MRO was expected to arrive earlier at the desired target phase, while after the maneuver it was anticipated to arrive slightly late.



(a) Pre-InSight Launch Through EDL



(b) Post-OSM-2 Through EDL

Figure 9: Evolution of the InSight EDL Target Phasing Offset

Also shown in Figure 9 are the different DSFs used in propagating the trajectory to estimate phasing offsets. The DSF adjusts the Mars-GRAM atmospheric model used for prediction. Since MRO's battery charging had become a concern following the OTM-49 (September 13, 2017) the solar arrays did not get parked in spite of the near perihelion distances. Instead, they continued to track the Sun. This solar array configuration was different from practice during the previous Mars years when a fixed configuration was utilized to help extend the gimbal life. This sun-track mode in turn had increased the effective area subjected to atmospheric drag, returning the phasing offsets to near expected levels. The first dust storm expanded into a PEDE starting around July 7, 2018 and lasted until about September 26, 2018. Towards the end of this PEDE a regional dust storm (B-storm) had begun near the southern lower latitudes around September 14, 2018 and lasted to about October 8, 2018. During this PEDE the DSF went from near 1.0 to about 0.56 as the dust activity faded into the background and overlapped with the beginning of the B-storm. However, there was not enough propagation time thereafter to have a significant impact on the final phasing offset.

Table 4 gives the phasing offset values as computed with each orbit solution used in response to the ERTFs leading to InSight's arrival at Mars (see column highlighted in yellow). The average DSF and 3-σ navigation timing uncertainty values are also provided for each phasing offset entry. Additionally, the table presents the OD data cut-off time and the number of days to the InSight overflight time for each entry. The OTM-50 design purposely removed about 43 minutes of the predicted phasing offset. This was based on the 12.5 minutes timing uncertainty at the time of the maneuver design DCO. The phasing offset started diminishing as the PEDE started to subside soon after OTM-50 was performed. The next phasing maneuver OTM-51 was designed to remove the remaining offset of about 2.41 minutes. Effects on phasing from the B-storm was minimal due to reduced propagation time. The final reconstructed timing offset value of −8.41 sec is highlighted in yellow at the bottom of the table. Note that ERTF-15 was the last ERTF used for OSM designs; subsequent ERTF deliveries were used for tracking purposes only and phasing offsets from those files are presented in the last column of the table.

Table 4: Evolution of MRO Phasing Offset from InSight EDL Target

ERTF for Phasing / Post-OSM Status *Post-ERTF-15 Tracking*	OD Data Cut-off (ET)	Days to EDL from DCO	Avg. DSF	3σ Nav. Timing Unc.	Phasing Offset from EDL Target + (early) − (late)	Post-ERTF-15 Phasing Offset Tracking + (early) − (late)
ERTF-01a	09-APR-2018 14:54:00	231.2	1.00	59.8 min	+47.12 min	
ERTF-02	14-MAY-2018 14:40:00	196.2	1.00	43.1 min	+46.66 min	
ERTF-03	29-MAY-2018 12:42:00	181.3	1.00	36.8 min	+46.07 min	
ERTF-04	04-JUN-2018 13:40:00	175.2	1.00	34.4 min	+46.51 min	
ERTF-05	18-JUN-2018 14:15:00	161.2	1.00	29.1 min	+47.12 min	
ERTF-06	28-JUN-2018 11:40:00	151.3	1.00	25.7 min	+48.32 min	
ERTF-07	12-JUL-2018 12:10:00	137.3	1.00	21.1 min	+51.42 min	
ERTF-08	26-JUL-2018 10:55:00	123.4	1.00	17.1 min	+53.59 min	
ERTF-09	06-AUG-2018 14:20:00	112.2	1.00	14.1 min	+55.62 min	
ERTF-10	13-AUG-2018 10:00:00	105.4	1.00	12.5 min	+55.23 min	
OSM-1/OTM-50 (22-AUG-2018 12:26:59 ET): designed to remove 42.73 min of offset (12.5 min remaining)						
Post-OSM-1 Status	22-AUG-2018 18:45:00	96.0	1.00	10.3 min	+10.74 min	
ERTF-11	30-AUG-2018 15:53:30	88.2	1.00	6.9 min	+10.78 min	
ERTF-12	10-SEP-2018 13:46:00	77.2	0.90	5.3 min	+7.07 min	
ERTF-13	27-SEP-2018 15:10:00	60.2	0.75	3.2 min	+3.51 min	
ERTF-14	08-OCT-2018 15:29:00	49.2	0.75	2.1 min	+3.37 min	
ERTF-15	15-OCT-2018 14:53:00	42.2	0.62	1.6 min	+2.41 min	
OSM-2/OTM-51 (24-OCT-2018 13:02:55 ET): designed to remove remaining offset						
Post-OSM-2 Status	24-OCT-2018 19:29:00	33.0	0.62	58.1 sec	+0.03 sec	
ERTF-15, *ERTF-16*	05-NOV-2018 14:23:00	21.2	0.62	24.1 sec	−4.05 sec	*−4.15 sec*
ERTF-15, *ERTF-17*	08-NOV-2018 10:42:00	18.4	0.58	18.0 sec	−7.65 sec	*−7.62 sec*
ERTF-15, *ERTF-17*	12-NOV-2018 14:05:00	14.2	0.56	10.9 sec	−8.72 sec	*−8.69 sec*
ERTF-15, *ERTF-18*	15-NOV-2018 14:15:00	11.2	0.56	6.8 sec	−8.71 sec	*−8.71 sec*
ERTF-15, *ERTF-19*	20-NOV-2018 11:45:00	6.3	0.56	2.2 sec	−8.28 sec	*−8.24 sec*
ERTF-15, *ERTF-19*	23-NOV-2018 21:15:00	2.9	0.56	0.51 sec	−8.40 sec	*−8.37 sec*
ERTF-15, *ERTF-20*	26-NOV-2018 06:30:00	0.5	0.56	0.03 sec	−8.41 sec	*−15.69 sec*
MRO Reconstruction at InSight EDL Target		0.0	0.56	0.0 sec	**−8.41 sec**	*−15.68 sec*

In addition to designing maneuvers to achieve the desired phasing conditions, and tracking the phasing offset after the second phasing maneuver using newer ERTFs, the MRO Navigation Team was tasked to perform OD three days prior to InSight's final maneuver TCM-6. This MRO OD was to assist the InSight Team with their Go/No-Go decision for TCM-6.

INSIGHT LANDING

The InSight lander successfully landed on Mars on November 26, 2018. The expected times of entry and touch down were 19:40:13 ET and 19:46:41 ET, respectively, per ERTF-20 (final). Even though the drag ΔV was expected to be higher than at previous relay support periods, it did not rise to those anticipated levels, as seen in Figure 10. This lower-than-expected drag ΔV was probably due to the decreased solar activity (near solar minimum). The drag ΔV averaged over 39 orbits during the InSight EDL period is shown in red in Figure 10 (Mars Year 34) . For comparison, the drag ΔV during a similar time frame in the previous Mars year (MY 33) is indicated in dark blue. Also shown are the periods of the PEDE and regional dust B-storm.

Following the InSight EDL time frame, OTM-52 (OCM-4) was used to redirect MRO towards achieving 3:15 PM LMST at the time of Mars 2020 EDL (February 18, 2021). This maneuver also included a pro-velocity component in order to resume the GTW control. The GTW error had built up to about 140 km during the InSight phasing support period. Thus the pro-velocity in-plane component countered the drag effects and PSO was reestablished to resume normal science operations.

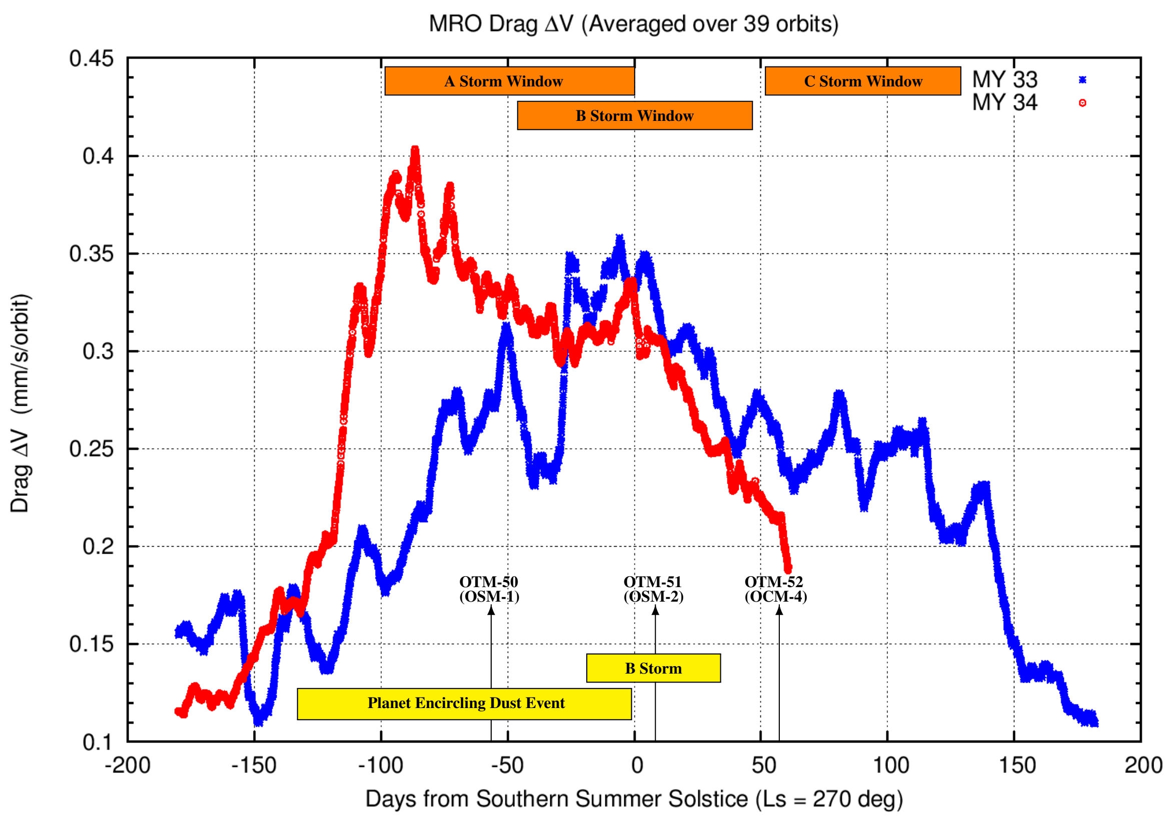


Figure 10: MRO Drag ΔV Per Orbit. *Days from Southern Summer Solstice (Day 0 corresponds to L_S = 270°)*

Planned InSight Overflights

The MRO project was expected to provide surface relay support after InSight EDL. MRO was to remain in its current orbit for at least one week. Table 5 shows the InSight overflight profile in the first 16 days following landing. Overflights with pass durations of at least 10 minutes and maximum elevation angles of at least 30 degrees are highlighted in yellow.

Table 5: Predicted InSight Overflights in First 16 Days

#	Pass Start (relative to InSight Landing)	Pass Start Time (ET)	Pass Length (min)	Max Elevation Angle (deg)	Max Elevation Time (ET)	MRO Off-Nadir Angle (deg)	Day/Night Pass
0	0.0 hrs (0.00 days)	26-NOV-2018 19:42:05.7884	12.59	20.99	26-NOV-2018 19:48:15.8363	59.86	Day
1	1.9 hrs (0.08 days)	26-NOV-2018 21:35:26.6598	8.33	4.81	26-NOV-2018 21:39:30.2641	-67.31	Day
2	12.2 hrs (0.51 days)	27-NOV-2018 07:49:19.9878	11.37	12.66	27-NOV-2018 07:55:07.2900	-64.61	Night
3	14.0 hrs (0.58 days)	27-NOV-2018 09:40:49.8734	10.71	10.03	27-NOV-2018 09:46:13.7301	65.70	Night
4	24.4 hrs (1.01 days)	27-NOV-2018 20:01:26.6410	10.64	9.87	27-NOV-2018 20:06:41.3161	65.80	Day
5	26.2 hrs (1.09 days)	27-NOV-2018 21:52:13.9859	11.39	12.78	27-NOV-2018 21:57:47.5412	-64.54	Day
6	36.5 hrs (1.52 days)	28-NOV-2018 08:09:11.0770	8.23	4.73	28-NOV-2018 08:13:21.3841	-67.31	Night
7	38.3 hrs (1.60 days)	28-NOV-2018 09:58:11.9033	12.64	21.37	28-NOV-2018 10:04:37.3745	59.55	Night
8	48.7 hrs (2.03 days)	28-NOV-2018 20:21:43.1008	6.76	2.89	28-NOV-2018 20:25:04.9580	67.59	Day
9	50.5 hrs (2.10 days)	28-NOV-2018 22:09:42.3948	12.98	26.79	28-NOV-2018 22:16:01.9194	-55.75	Day
10	62.6 hrs (2.61 days)	29-NOV-2018 10:15:59.5962	13.59	46.66	29-NOV-2018 10:22:56.5832	39.45	Night
11	74.8 hrs (3.12 days)	29-NOV-2018 22:27:36.6609	13.67	61.71	29-NOV-2018 22:34:15.9545	-26.05	Day
12	86.9 hrs (3.62 days)	30-NOV-2018 10:34:10.1688	13.78	73.26	30-NOV-2018 10:41:13.8779	-15.56	Night
13	99.1 hrs (4.13 days)	30-NOV-2018 22:45:55.2851	13.64	55.04	30-NOV-2018 22:52:33.8401	32.14	Day
14	111.2 hrs (4.63 days)	01-DEC-2018 10:52:46.1543	13.23	31.30	01-DEC-2018 10:59:32.5939	-52.36	Night
15	113.1 hrs (4.71 days)	01-DEC-2018 12:47:40.6945	5.56	1.78	01-DEC-2018 12:50:24.7371	67.66	Night
16	123.4 hrs (5.14 days)	01-DEC-2018 23:04:39.6574	12.87	24.65	01-DEC-2018 23:10:57.2270	57.37	Day
17	125.3 hrs (5.22 days)	02-DEC-2018 00:58:41.7335	7.24	3.38	02-DEC-2018 01:02:12.9511	-67.57	Day
18	135.5 hrs (5.65 days)	02-DEC-2018 11:11:48.4962	11.84	15.03	02-DEC-2018 11:17:50.4289	-63.41	Night
19	137.4 hrs (5.72 days)	02-DEC-2018 13:03:49.8273	10.11	8.25	02-DEC-2018 13:08:54.3760	66.33	Night
20	147.7 hrs (6.16 days)	02-DEC-2018 23:23:51.9248	11.18	11.83	02-DEC-2018 23:29:21.7956	65.00	Day
21	149.6 hrs (6.23 days)	03-DEC-2018 01:15:11.9272	10.87	10.66	03-DEC-2018 01:20:29.9249	-65.49	Day
22	159.9 hrs (6.66 days)	03-DEC-2018 11:31:25.8848	9.14	6.25	03-DEC-2018 11:36:03.8855	-66.96	Night
23	161.7 hrs (6.74 days)	03-DEC-2018 13:21:03.0755	12.31	18.21	03-DEC-2018 13:27:17.9545	61.55	Night
24	172.1 hrs (7.17 days)	03-DEC-2018 23:43:49.3001	7.90	4.24	03-DEC-2018 23:47:44.3700	67.41	Day
25	173.9 hrs (7.24 days)	04-DEC-2018 01:32:31.9843	12.71	22.70	04-DEC-2018 01:38:43.5179	-58.67	Day
26	184.2 hrs (7.68 days)	04-DEC-2018 11:53:17.3025	1.89	0.21	04-DEC-2018 11:54:14.9989	-67.76	Night
27	186.0 hrs (7.75 days)	04-DEC-2018 13:38:44.5342	13.45	38.72	04-DEC-2018 13:45:36.9774	46.24	Night
28	198.2 hrs (8.26 days)	05-DEC-2018 01:50:19.7284	13.58	50.54	05-DEC-2018 01:56:56.2163	-36.07	Day
29	210.3 hrs (8.76 days)	05-DEC-2018 13:56:48.7035	13.80	88.14	05-DEC-2018 14:03:53.1704	-1.80	Night
30	222.5 hrs (9.27 days)	06-DEC-2018 02:08:31.5920	13.70	67.08	06-DEC-2018 02:15:11.6826	21.23	Day
31	234.6 hrs (9.77 days)	06-DEC-2018 14:15:17.7335	13.42	37.22	06-DEC-2018 14:22:10.2735	-47.59	Night
32	236.5 hrs (9.85 days)	06-DEC-2018 16:11:18.1143	3.50	0.60	06-DEC-2018 16:12:59.4177	67.71	Night
33	246.8 hrs (10.28 days)	07-DEC-2018 02:27:09.0478	13.10	28.96	07-DEC-2018 02:33:32.8171	54.20	Day
34	248.7 hrs (10.36 days)	07-DEC-2018 04:21:58.5466	5.90	2.08	07-DEC-2018 04:24:49.5860	-67.74	Day
35	258.9 hrs (10.79 days)	07-DEC-2018 14:34:13.0635	12.24	17.66	07-DEC-2018 14:40:27.4945	-61.93	Night
36	260.8 hrs (10.87 days)	07-DEC-2018 16:26:46.0960	9.41	6.65	07-DEC-2018 16:31:28.8223	66.81	Night
37	271.1 hrs (11.30 days)	08-DEC-2018 02:46:13.4251	11.64	13.98	08-DEC-2018 02:51:56.2320	63.99	Day
38	273.0 hrs (11.37 days)	08-DEC-2018 04:38:05.5765	10.28	8.81	08-DEC-2018 04:43:06.1108	-66.20	Day
39	283.2 hrs (11.80 days)	08-DEC-2018 14:53:39.3937	9.89	7.86	08-DEC-2018 14:58:40.3795	-66.50	Night
40	285.1 hrs (11.88 days)	08-DEC-2018 16:43:49.4788	11.95	15.54	08-DEC-2018 16:49:52.4065	63.08	Night
41	295.4 hrs (12.31 days)	09-DEC-2018 03:05:56.2494	8.82	5.65	09-DEC-2018 03:10:17.8440	67.13	Day
42	297.3 hrs (12.39 days)	09-DEC-2018 04:55:16.5756	12.40	19.36	09-DEC-2018 05:01:19.0303	-60.87	Day
43	307.6 hrs (12.82 days)	09-DEC-2018 15:14:25.0558	4.80	1.40	09-DEC-2018 15:16:50.4989	-67.72	Night
44	309.4 hrs (12.89 days)	09-DEC-2018 17:01:24.5659	13.28	32.55	09-DEC-2018 17:08:11.2751	51.28	Night
45	321.5 hrs (13.40 days)	10-DEC-2018 05:12:57.7291	13.45	41.87	10-DEC-2018 05:19:30.5563	-43.61	Day
46	333.7 hrs (13.90 days)	10-DEC-2018 17:19:22.5331	13.79	77.06	10-DEC-2018 17:26:26.5618	11.91	Night
47	345.8 hrs (14.41 days)	11-DEC-2018 05:31:02.9967	13.73	81.01	11-DEC-2018 05:37:43.7756	8.39	Day
48	358.0 hrs (14.91 days)	11-DEC-2018 17:37:44.7745	13.57	44.47	11-DEC-2018 17:44:42.0261	-41.46	Night
49	370.2 hrs (15.42 days)	12-DEC-2018 05:49:33.6307	13.29	34.14	12-DEC-2018 05:56:02.4849	50.14	Day
50	372.1 hrs (15.50 days)	12-DEC-2018 07:45:24.1685	4.05	0.88	12-DEC-2018 07:47:20.0556	-67.82	Day
51	382.3 hrs (15.93 days)	12-DEC-2018 17:56:33.2933	12.57	20.62	12-DEC-2018 18:02:58.3168	-60.10	Night
52	384.2 hrs (16.01 days)	12-DEC-2018 19:49:39.0915	8.62	5.20	12-DEC-2018 19:53:56.9260	67.16	Night

InSight Landing Site

The InSight landing on Mars was very successful following the final InSight maneuver, TCM-6. However, it landed about 20 km west of the target and the landing time was about 40 sec early. The difference in the actual landing location delayed MRO's plan to image InSight on the ground as the roll angles changed. After refining InSight's landing location, MRO's CTX and HiRISE camera were used to image the lander and parts such as the parachute, back shell and heat shield a few days later. Shown in Figure 11 below is an image taken by HiRISE on May 30, 2014 . It is annotated to indicate the relative location (within about 1000 feet from each other) of the landed parts of the InSight mission.

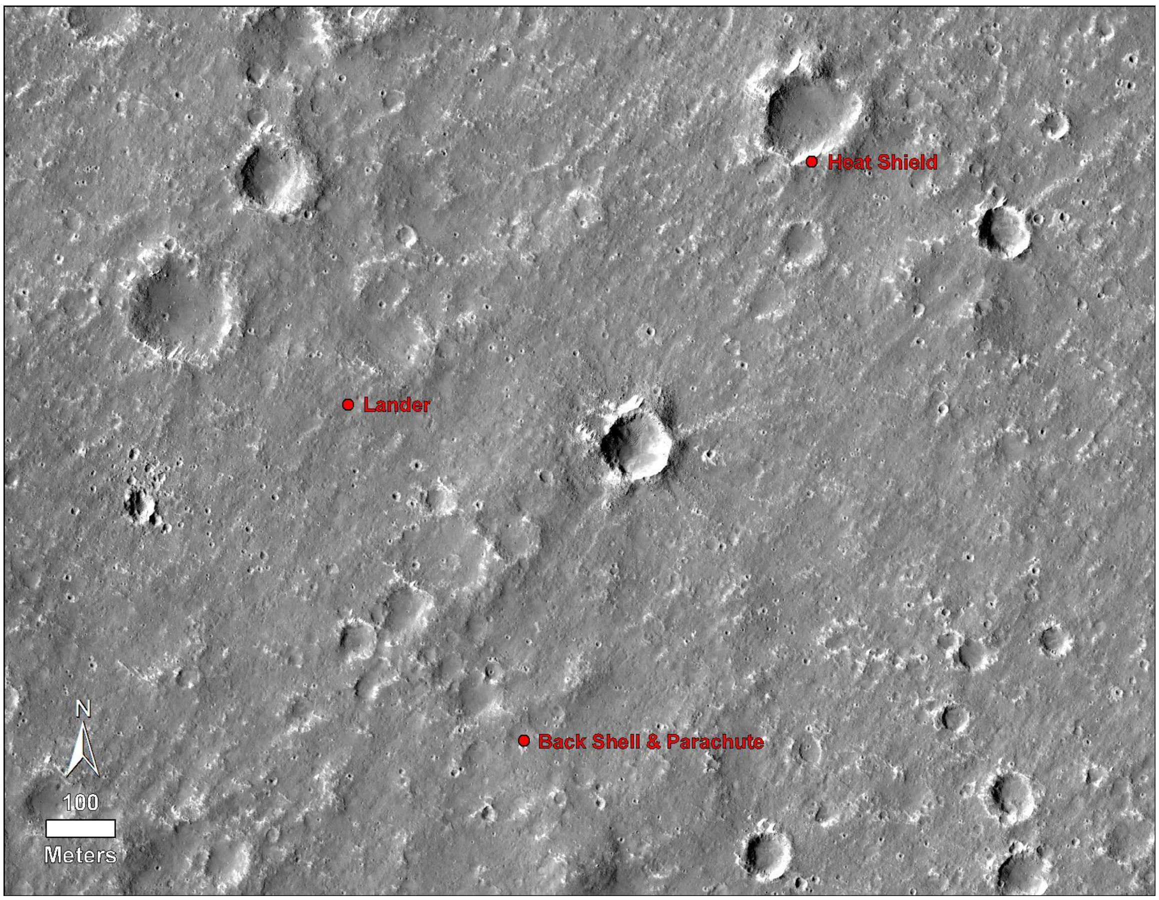
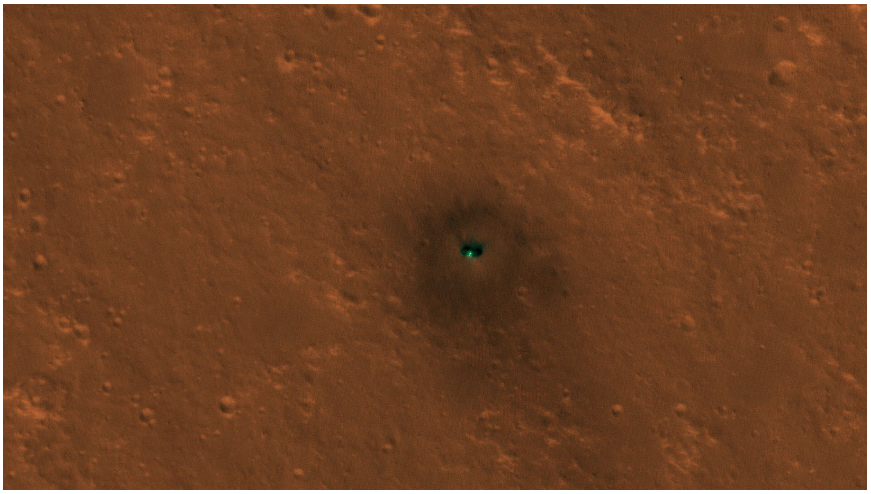
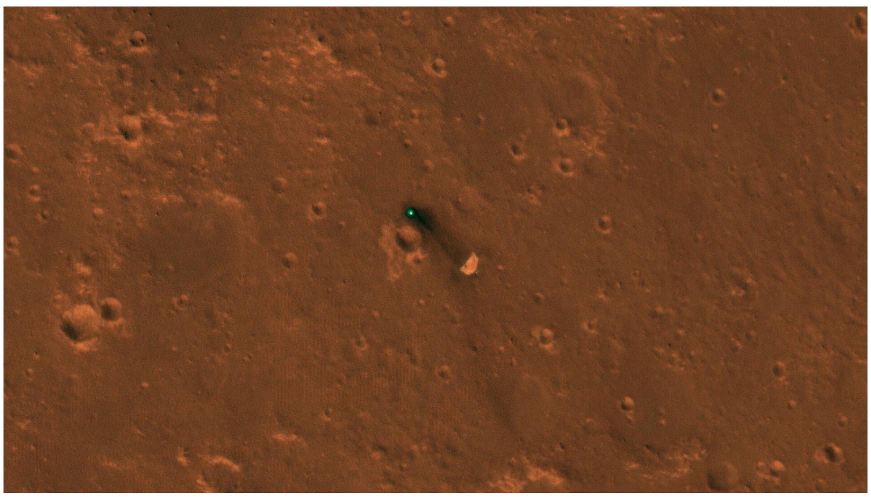


Figure 11: An annotated image of the surface of Mars, taken by HiRISE camera on May 30, 2014. The annotations – added after InSight landed on November 26, 2018 – display the locations of the InSight lander, its heat shield and parachute. Source: NASA/JPL-Caltech/University of Arizona.

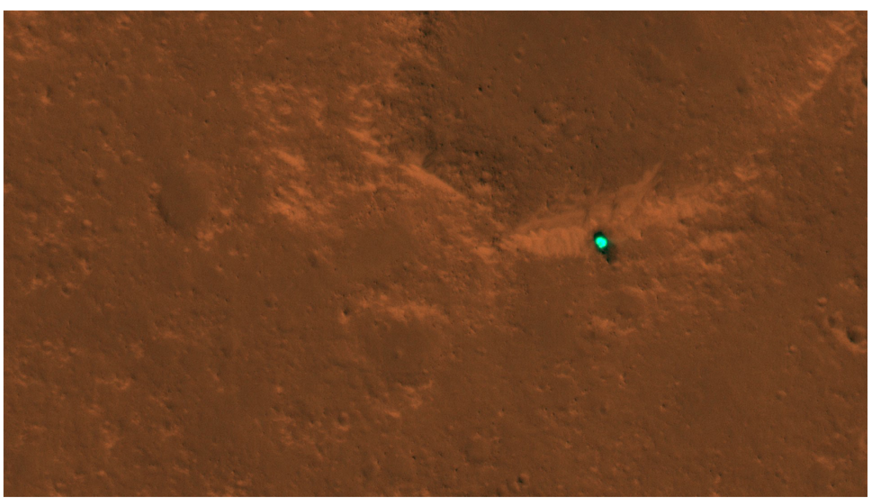
The HiRISE camera took images on December 6 and 11, 2018 that revealed three separate locations showing the lander (Figure 12a), the parachute (Figure 12b), and the heat shield (Figure 12c). The overflight information provided by the MRO Navigation Team (see Table 5) also aided in the planning of these images.



(a) InSight Lander



(b) Parachute & Back Shell



(c) Heat Shield

Figure 12: Images of the InSight Landing Site Taken by HiRISE on December 6 and 11, 2018. Source: NASA/JPL-Caltech/University of Arizona.

RETURN TO MRO PRIMARY SCIENCE ORBIT AFTER INSIGHT SUPPORT

Performed in the pro-velocity direction, the two phasing maneuvers OTM-50 and OTM-51 aided in keeping the GTW error from growing too large. Instead, the GTW error stayed to within about 140 km as compared to the Comet Siding Spring Risk mitigation effort when it drifted to about 240 km. These phasing maneuvers moved the GTW error further west and outside the mission requirement of $\pm$60 km for a brief period of time, as can be seen in Figure 8. Meanwhile, the Local Mean Solar Time (LMST) had been on a drift towards 2:52 PM required for InSight EDL after the execution of an inclination-change maneuver OTM-48 (OCM-3) on March 22, 2017. Following InSight EDL support, another inclination-change maneuver (OCM-4) is required to achieve 3:15 PM LMST for Mars 2020 EDL. Since the Local True Solar Time (LTST) minimum with the current orbit was expected to go below 2 PM in late January 2019, the MRO Navigation Team recommended performing OCM-4 as early as possible following the InSight EDL support. If the MRO project decides to stay at 3:15 PM LMST beyond Mars 2020 EDL, then another OCM will be executed to arrest the LMST's upward drift.[7] OTM-52 (OCM-4) was successfully executed on December 12, 2018 just 16 days after InSight EDL. This maneuver was performed at the descending equator crossing with a total ΔV of about 1.4 m/s to change the nodal drift such that 3:15 PM LMST is achieved by February 18, 2021 (Mars 2020 EDL) and included a large in-plane component to control the GTW error to within $\pm$60 km. OTM-52 performed well within expectations (2.1% overburn). For details on OCM-4 and the maneuver plan beyond Mars 2020 EDL support, see Reference 7.

CONCLUSION

MRO successfully provided relay support to InSight during its EDL phase. This was due to the accurate phasing that MRO achieved. Following the landing by InSight, MRO continues to provide excellent relay support for its surface operations. In addition, MRO's CTX and HiRISE cameras made observations and images of the different landed parts of the InSight lander, including the parachute, back shell and heat shield. The navigation plan to phase MRO to the prescribed InSight EDL target location was successfully implemented with the executions of the two pro-velocity maneuvers OTM-50 and OTM-51 without utilizing a third maneuver in close proximity to EDL. Despite the Planet Encircling Dust Event that materialized in July 2018, the regional dust B-storm that followed and the execution errors in the final phasing maneuver, MRO was only about 8.41 seconds late (per ERTF-15 used for OTM-51) from its intended target. However, the actual final offset was 15.67 seconds later than the target provided in ERTF-20, which incorporated InSight's final maneuver TCM-6. The predicted phasing offset was well within InSight phasing requirement of $\pm$30 seconds and MRO Navigation's 3-σ timing uncertainty of 1.6 minutes following the final phasing maneuver, OTM-51. This phasing accuracy can be better appreciated in comparison to the almost 60 seconds timing accuracy achieved by MRO to avoid the Comet Siding Spring's incoming particle flux as it passed by Mars on October 19, 2014[4] and about 9 seconds when supporting MSL EDL in August 2012.[4] The trajectory from the final orbit determination by the MRO Navigation Team on November 23, 2018 was provided to the InSight Team which aided in their TCM-6 Go/No-Go assessments. Additionally, the MRO Navigation Team provided the overflight information which assisted in the efforts to image the landed parts of InSight mission. In summary, the MRO Navigation Team was able to achieve the InSight EDL target parameters well within the phasing requirement which led to successful support of InSight surface operations thereafter.

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

APPENDIX A: EDL RELAY TARGET FILES

Coordination between the MRO Navigation Team and InSight Navigation Team was established prior to the launch of InSight. The InSight Team provided ERTF files which included the EDL target time and corresponding latitude (see Reference 8). In return, the MRO Navigation Team supplied the predicted MRO trajectories based on current orbit solutions through the InSight EDL support period. Table 6 presents the EDL Relay Target File (ERTF) history, beginning with ERTF-01. ERTF-15 (highlighted in Table 6) was used for designing OTM-51, the final OSM performed to phase MRO to the InSight EDL target.

Table 6: History of InSight EDL Relay Targets for MRO Phasing

ERTF	Delivery Date	Days to Target	MRO Relay Target Conditions (2000 IAU Mars Fixed)			Comments
			Epoch (ET)	Latitude (deg)	LMST	
01a	06-Apr-2018	234	26-Nov-2018 19:40:06.2191	−18.8984	14:50:33	Launch − 30d, open middle phasing
01b	06-Apr-2018	234	26-Nov-2018 19:40:06.2191	−23.9182	14:50:33	Open south phasing
01c	06-Apr-2018	234	26-Nov-2018 19:40:06.2191	−13.9658	14:50:33	Open north phasing
01d	06-Apr-2018	234	26-Nov-2018 20:01:02.0880	−13.6332	14:50:33	Open latest north phasing
01e	29-Apr-2018	211	26-Nov-2018 20:01:02.0880	−26.6056	14:50:33	Open latest south phasing
02	09-May-2018	201	26-Nov-2018 19:40:09.4412	−19.4513	14:50:53	Launch + 5d, middle phasing
03	23-May-2018	187	26-Nov-2018 19:40:08.4088	−19.4847	14:50:46	Post-TCM-1
04	30-May-2018	180	26-Nov-2018 19:40:26.5421	−19.5940	14:50:44	Update to center nominal within landing ellipse
05	13-Jun-2018	166	26-Nov-2018 19:40:26.7214	−19.6149	14:50:42	Middle phasing target chosen
06	27-Jun-2018	152	26-Nov-2018 19:40:18.7070	−19.5646	14:50:42	Post-thruster-calibration, new landing site
07	11-Jul-2018	138	26-Nov-2018 19:40:15.5920	−19.5543	14:50:42	Correction to wind model for EDL modeling
08	25-Jul-2018	124	26-Nov-2018 19:40:15.2312	−19.5646	14:50:42	Designed TCM-2
09	30-Jul-2018	119	26-Nov-2018 19:40:13.1347	−19.5653	14:50:42	Post-TCM-2
10	08-Aug-2018	110	26-Nov-2018 19:40:13.3889	−19.5624	14:50:42	OSM-1 target (partial phasing)
11	22-Aug-2018	96	26-Nov-2018 19:40:13.4298	−19.5550	14:50:41	
12	05-Sep-2018	82	26-Nov-2018 19:40:13.4613	−19.5552	14:50:41	
13	19-Sep-2018	68	26-Nov-2018 19:40:13.4516	−19.5584	14:50:41	
14	03-Oct-2018	54	26-Nov-2018 19:40:13.4276	−19.5599	14:50:40	
15	17-Oct-2018	40	26-Nov-2018 19:40:13.4776	−19.5547	14:50:40	Post-TCM-3, final phasing request, OSM-2 tgt.
16	31-Oct-2018	26	26-Nov-2018 19:40:13.4039	−19.5535	14:50:40	
17	07-Nov-2018	19	26-Nov-2018 19:40:13.3786	−19.5616	14:50:40	
18	13-Nov-2018	13	26-Nov-2018 19:40:13.3477	−19.5619	14:50:40	Atmosphere & landing site updates
19	20-Nov-2018	6	26-Nov-2018 19:40:13.3388	−19.5640	14:50:40	Atmosphere & landing site updates
20	25-Nov-2018	1	26-Nov-2018 19:40:13.3470	−19.1708	14:50:40	Designed TCM-6

ERTF-15 was provided to the MRO Navigation Team by the InSight Team for the final phasing maneuver design while ERTF-20 incorporated InSight's TCM-6 (see Figure 13). These files contain the requested relay target, as well as the predicted entry and landing epochs and coordinates.

```
----------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
----------------------------------------------------------------
Data generated on Wed Oct 17 10:33:08 2018 PDT by M. Wallace,
NASA Jet Propulsion Laboratory

NSYT SPK File: nsyt_spk_cruise_od089_v1_approach2surface.bsp
MRO SPK File:
spk_psp_20181008-20181213_20181008_ERTF14_forInSight_traj_only.bsp

************************************************************
*   MRO RELAY TARGETS (2000 IAU Mars Fixed)
*   Epoch              : 26-NOV-2018 19:40:13.4776 ET
*   LMST (Asc.Eq.Cross): 14:50:40
*   Latitude           : -19.5547 deg
************************************************************

NSYT Data (2000 IAU Mars Fixed)
Entry Epoch                 : 26-NOV-2018 19:40:13.4776 ET
     Entry Latitude         : 1.7152 deg
     Entry Longitude        : 124.5611 deg
Landing Epoch               : 26-NOV-2018 19:46:58.9678 ET
     Landing Latitude       : 4.5102 deg
     Landing Longitude      : 135.9910 deg
     Landing Radius         : 3393.0620 km

MRO Data - Keplerian Osculating Elements (2000 IAU Mars Pole)
Entry Epoch                 : 26-NOV-2018 19:40:13.4776 ET
     Semimajor Axis         : 3663.6992 km
     Eccentricity           : 0.009595
     Inclination            : 92.5900 deg
     RAAN                   : -165.5901 deg
     Arg. of Periapsis      : 270.3522 deg
     Mean Anomaly           : 69.0412 deg
     True Anomaly           : 70.0723 deg

MRO Data - Spherical Coordinates (2000 IAU Mars Fixed)
Entry Epoch                 : 26-NOV-2018 19:40:13.4776 ET
     Target Latitude        : -19.5547 deg
     Target Longitude       : 148.3097 deg
     LMST (Asc.Eq.Cross)    : 14:50:40
     LTST (Asc.Eq.Cross)    : 14:12:52
Landing Epoch               : 26-NOV-2018 19:46:58.9678 ET
     MRO Lat. at Landing    : 2.1775 deg
     MRO Lon. at Landing    : 145.6430 deg
```

(a) InSight ERTF-15 (Used for Final MRO Phasing Maneuver)

```
----------------------------------------------------------------
EDL RELAY TARGETS FILE (ERTF)
----------------------------------------------------------------
Data generated on Sun Nov 25 10:31:57 2018 PST by M. Wallace,
NASA Jet Propulsion Laboratory

NSYT SPK File: nsyt_spk_cruise_od115_v1_approach2surface.bsp
MRO SPK File:
spk_psp_20181120-20181213_20181120_forInSight_traj_only.bsp

************************************************************
*   MRO RELAY TARGETS (2000 IAU Mars Fixed)
*   Epoch              : 26-NOV-2018 19:40:13.3470 ET
*   LMST (Asc.Eq.Cross): 14:50:40
*   Latitude           : -19.1708 deg
************************************************************

NSYT Data (2000 IAU Mars Fixed)
Entry Epoch                 : 26-NOV-2018 19:40:13.3470 ET
     Entry Latitude         : 1.7105 deg
     Entry Longitude        : 124.5549 deg
Landing Epoch               : 26-NOV-2018 19:46:40.5970 ET
     Landing Latitude       : 4.4959 deg
     Landing Longitude      : 135.9386 deg
     Landing Radius         : 3393.0998 km

MRO Data - Keplerian Osculating Elements (2000 IAU Mars Pole)
Entry Epoch                 : 26-NOV-2018 19:40:13.3470 ET
     Semimajor Axis         : 3663.8102 km
     Eccentricity           : 0.009603
     Inclination            : 92.5899 deg
     RAAN                   : -165.5911 deg
     Arg. of Periapsis      : 270.4383 deg
     Mean Anomaly           : 69.3366 deg
     True Anomaly           : 70.3706 deg

MRO Data - Spherical Coordinates (2000 IAU Mars Fixed)
Entry Epoch                 : 26-NOV-2018 19:40:13.3470 ET
     Target Latitude        : -19.1708 deg
     Target Longitude       : 148.2897 deg
     LMST (Asc.Eq.Cross)    : 14:50:40
     LTST (Asc.Eq.Cross)    : 14:12:52
Landing Epoch               : 26-NOV-2018 19:46:40.5970 ET
     MRO Lat. at Landing    : 1.5840 deg
     MRO Lon. at Landing    : 145.7436 deg
```

(b) InSight ERTF-20 (InSight TCM-6 Design Incorporated)

Figure 13: InSight ERTFs Used for MRO Final Phasing and Offset Tracking

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